Performance Assessment of a Piezoelectric Footstep Energy Harvesting System for Sustainable Power Generation

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Abstract. This paper presents the design, modelling, and experimental evaluation of a piezoelectric footstep energy harvesting system intended to generate low-voltage electrical power from human motion. The study examines the use of piezoelectric transducers arranged within a mechanical platform to convert mechanical stress into electrical output suitable for small-scale applications. A comprehensive literature review was conducted to evaluate piezoelectric materials, energy management circuits, and hybrid harvesting solutions. The methodology integrates theoretical calculations, rectification circuitry, load testing, and prototype development. Experimental results confirmed that the system can generate measurable AC voltage peaks during footstep loading and deliver regulated DC power after rectification. The findings demonstrate the feasibility of piezoelectric harvesting for lighting, sensor powering, and low-energy IoT applications, supporting sustainable and decentralized energy solutions for pedestrian-dense environments.

Keywords: Piezoelectric generator, Energy harvesting, Footstep power, Sustainable energy, PZT, PVDF, Power electronics.

1 Introduction

Increasing global energy demand, the rising cost of electricity, and the need to reduce environmental impact have motivated the search for alternative and sustainable energy sources [1], [2]. Piezoelectric energy harvesting, which converts mechanical vibrations or pressure into electrical energy, offers a promising solution for powering low-consumption devices in urban and pedestrian-dense environments [3]. Applications include smart walkways, self-powered sensors, wearable electronics, and autonomous monitoring systems [4].

In piezoelectric materials, mechanical stress produces an electric charge due to the displacement of internal dipoles [5]. This effect, shown in Figure 1, is harnessed in footstep power systems where pressure from human movement generates alternating voltage output. Integrating piezoelectric harvesting with energy-management circuits enables the storage or utilization of this energy for useful loads such as LED lighting or microcontrollers [6].

MECSRC 2025, May 01, Muscat, Oman
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DOI 10.4108/eai.1-5-2025.2361479

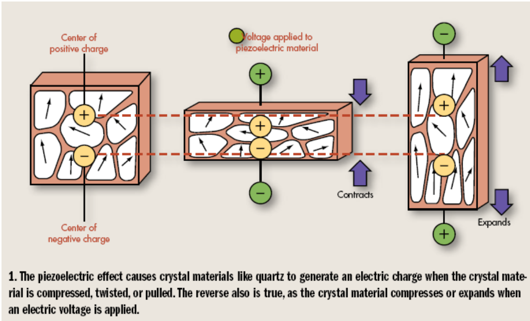

Fig. 1. Mechanism of piezoelectric effect. [7]

Commercial developments such as **Pavegen** have demonstrated large-scale piezoelectric walkways capable of powering street lighting, digital signage, and real-time data systems shown in Figure 2. These advancements highlight growing interest in pedestrian-based energy harvesting as a component of smart city infrastructure [8].

Fig. 2. Pavegen case study demonstrating real-world applications. [9]

The purpose of this study is to design, simulate, and experimentally validate a piezoelectric footstep platform suitable for small-scale power generation, while assessing system behaviour, voltage output characteristics, and overall feasibility within sustainable energy frameworks.

2 Literature Review

2.1 Piezoelectric Materials and Operating Principle

Piezoelectric materials generate an electric charge when subjected to mechanical strain, a phenomenon known as the direct piezoelectric effect. Figure 1 illustrates this mechanism, where deformation causes charge separation across the crystal lattice [10]. Commonly used materials include:

- PZT (Lead Zirconate Titanate): High piezoelectric coefficient, brittle, widely used in harvesting.
- PVDF (Polyvinylidene Fluoride): Flexible, lightweight, suitable for wearable harvesters.

A comparison of PZT and PVDF is shown in Figure 3.

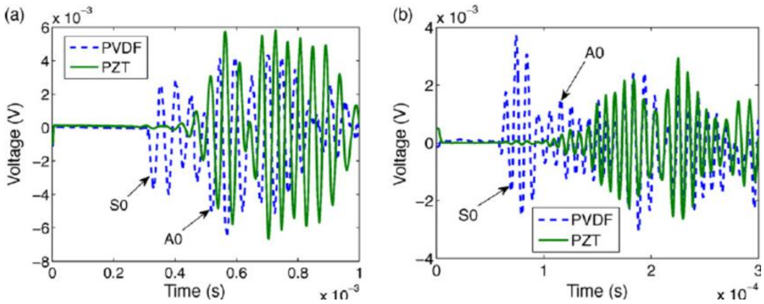

Fig. 3. Comparison between PZT and PVDF piezoelectric materials. [11]

PZT offers higher voltage output, whereas PVDF provides greater mechanical resilience and flexibility. Hybrid composite materials have emerged to balance efficiency and structural durability [11].

2.2 Applications of Piezoelectric Energy Harvesting

Piezoelectric harvesting is applied in a variety of fields, including:

- Smart flooring systems
- Railway vibration harvesting
- Structural health monitoring
- Human-motion powered gadgets
- Automated lighting systems

Typical application areas are summarized in Figure 4.

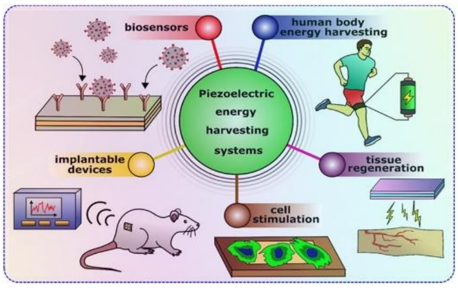

Fig. 4. Applications of piezoelectric harvesting. [12]

Large-scale systems, such as those developed by Pavegen shown in Figure 4, demonstrate the potential for urban installation, contributing to energy generation and data analytics in smart city environments [12].

2.3 Hybrid Piezoelectric–Solar Harvesting Systems

Hybrid systems integrate piezoelectric transducers with photovoltaic panels to maximize output under varying environmental and load conditions. As shown in Figure 5, combining two harvesting mechanisms increases reliability and improves energy availability for storage devices such as supercapacitors and Li-ion batteries [13].

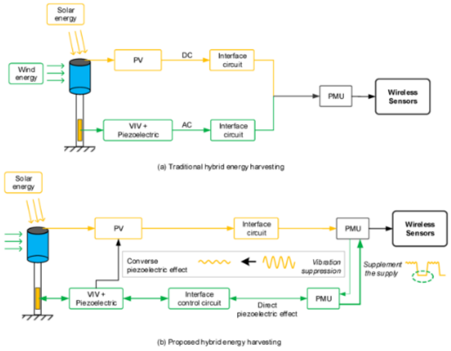

Fig. 5. Hybrid solar–piezoelectric energy harvesting system. [14]

Studies indicate that hybrid systems can boost power generation by 30–60% depending on usage patterns and ambient light intensity [15].

2.4 Power Conditioning and Energy Management

Piezoelectric output is typically AC and requires rectification, filtering, and regulation to be useful. The energy management circuit used in this study is shown in Figure 6.

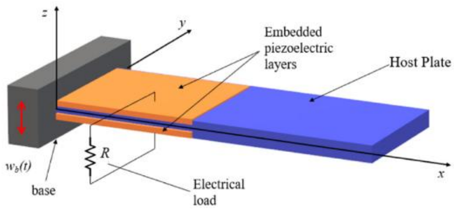

Fig. 6. Power management circuit using bridge rectifier, capacitor, and regulator. [16]

Key stages include:

- **AC to DC conversion** using a full-wave bridge
- **Energy smoothing** using capacitors
- **Voltage regulation** for stable DC output
- **Load interfacing** (LEDs, storage, sensors)

Efficient circuits reduce losses and improve overall system performance [13].

2.5 Alignment with Sustainable Development Goals (SDGs)

Piezoelectric footstep energy harvesting contributes to the United Nations Sustainable Development Goal **SDG 7: Affordable and Clean Energy**, illustrated in Figure 7.

Fig. 7. UN SDG 7: Affordable and Clean Energy. [17]

By converting human motion into usable electricity, such systems support micro-generation, smart infrastructure, and reduced dependence on fossil fuels [18].

2.6 Summary of Key Research Gaps

Based on the reviewed literature:

- Many studies focus on theoretical modelling, but fewer provide **practical prototype validation**.
- **Energy management circuits** vary widely in efficiency and require optimization.
- Long-term durability of piezoelectric materials under repeated loading needs deeper investigation.
- Output power remains low, requiring **load matching and improved mechanical design**.

This project addresses these gaps through a combined design–simulation–prototype approach.

3 Methodology

The methodology adopted in this study consists of three phases: (1) system design and modelling, (2) construction of the prototype footstep platform, and (3) experimental testing and data acquisition. A structured workflow is shown in Figure 8.

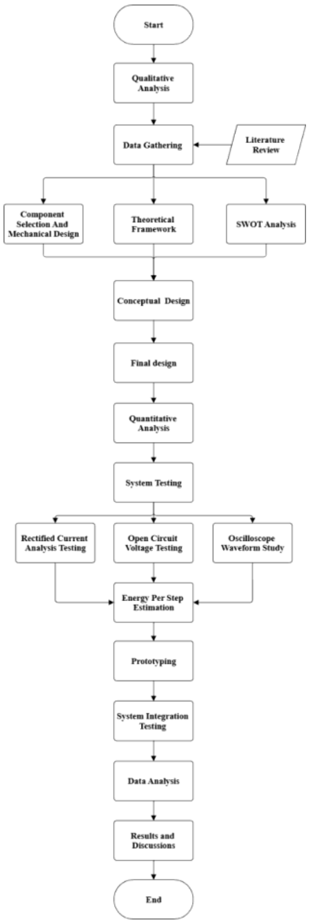

Fig. 8. Methodology workflow for system development.

3.1 System Design

The system was designed to generate electrical energy from mechanical pressure applied to the piezoelectric elements. The design incorporates:

- Piezoelectric transducers arranged beneath a rigid footstep plate
- A load-bearing frame
- A full-wave bridge rectifier
- Voltage smoothing capacitors

- DC output terminals for powering a load (LEDs)

A primary design requirement was to protect the piezoelectric elements from excessive deformation while maximizing strain transfer to enhance electrical output. The mechanical design also ensured uniform load distribution across the transducers.

3.2 Electronic Circuit Development

The electronic circuit includes three major stages:

1. **AC Voltage Generation:** Piezo discs produce AC voltage upon compression.
2. **Rectification:** A full-wave bridge rectifier converts the AC voltage into DC.
3. **Filtering and Storage:** A capacitor smooths the rectified signal to reduce ripple and stabilize the voltage before it is applied to a load.

The power conditioning circuit is shown in Figure 6. The final integrated circuit layout enables low-voltage DC output suitable for lighting small LEDs or powering low-power sensors.

3.3 Experimental Setup

A schematic of the experimental setup is shown in Figure 9. The system consists of:

- A mechanical housing containing multiple piezo discs
- A top plate for applying human footstep force
- A digital multimeter for voltage readings
- An oscilloscope for waveform observation
- LED load for output verification

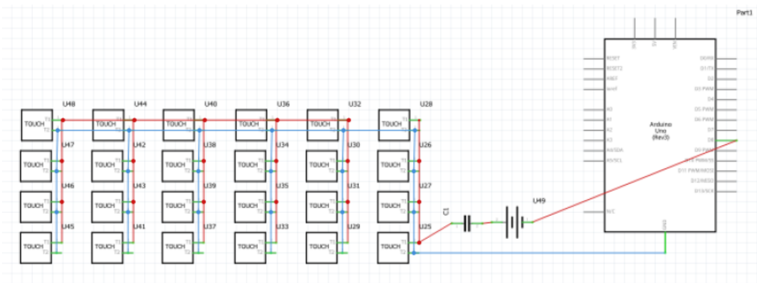

Fig. 9. Schematic representation of the experimental setup.

3.4 Prototype Development

The final prototype involved assembling the piezoelectric discs with the mechanical platform and electronics. Figure 10 shows the completed prototype used for testing.

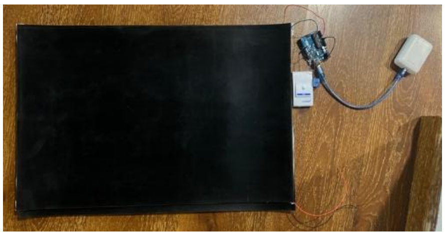

Fig. 10. Final assembled piezoelectric footstep prototype.

3.5 Data Collection Procedure

Testing involved applying footstep pressure repeatedly to the platform and recording the following:

- Peak AC voltage generated across piezo discs
- Rectified DC voltage after filtering
- Voltage behavior under repeated loading cycles
- Effectiveness of the rectification circuit
- Load behaviour when powering LEDs

Waveform analysis was performed using an oscilloscope to observe signal characteristics shown in Figure 11.

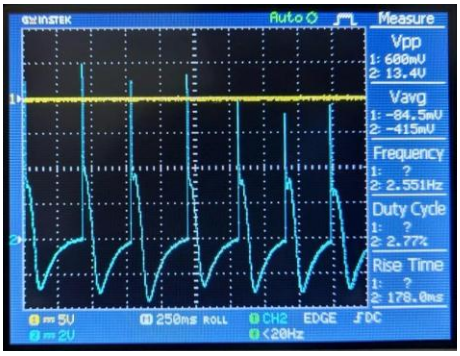

Fig. 11. Oscilloscope output showing AC waveform of piezoelectric voltage.

4 Results and Discussion

4.1 Voltage Output Characteristics

The piezoelectric discs produced AC voltage peaks when subjected to downward pressure. Output voltage increased proportionally with applied force, consistent with established piezoelectric principles [19], [20]. The oscilloscope waveform (Figure 10) confirmed sharp transient peaks characteristic of piezoelectric transducers undergoing impact loading.

Rectified DC voltage readings showed:

- Higher stability after filtering
- Sufficient power to drive multiple LEDs
- Ripple reduction due to capacitor smoothing

These results align with findings in [21], demonstrating that proper rectification significantly improves output usability.

4.2 Effectiveness of Rectification Circuit

The full-wave bridge rectifier converted the high-frequency AC pulses into DC voltage with increased efficiency compared to half-wave rectification. The improved performance supports literature stating that full-wave rectification enhances output by utilizing both positive and negative AC cycles [22], [23].

The capacitor effectively stored charges and reduced voltage fluctuations, enabling the system to provide a continuous supply to low-power loads.

4.3 Prototype Performance Evaluation

Observations from prototype testing include:

- Detectable voltage generation under normal walking pressure
- Voltage levels sufficient for LED illumination
- Quick response time of piezoelectric elements (~milliseconds)
- Durability of piezo discs under repeated loading cycles

While the output is not sufficient for high-power applications, it is suitable for:

- Indicator lights
- Small sensors
- Microcontroller-based IoT devices
- Low-power urban infrastructure

The output magnitude is comparable with similar studies in piezoelectric floor-based energy harvesting [24], [25].

4.4 Limitations

Key limitations identified:

- Output power is low and depends on user weight and step frequency
- Piezoelectric discs require mechanical reinforcement to prevent fatigue failure [26]
- Energy storage relies on external capacitor or battery systems
- AC voltage spikes require efficient protection circuitry [27]

5 Conclusion and Recommendations

This research successfully demonstrates the feasibility of generating small-scale electrical power from human footsteps using piezoelectric transducers. The system integrates mechanical design, piezoelectric materials, and electronic conditioning to produce usable DC output. Experimental testing confirmed:

- Reliable voltage generation under typical human walking loads
- Effective AC-to-DC conversion using the rectification circuit
- Sufficient output to power low-energy devices such as LEDs
- Clear potential for use in public walkways, malls, airports, and universities

The study contributes to the development of sustainable micro-energy systems and highlights the potential of piezoelectric harvesting in urban smart environments.

Recommendations are listed below:

1. Integrate a supercapacitor for improved energy storage.
2. Optimize the mechanical plate design to increase pressure transfer.
3. Use series–parallel piezo configurations to boost power output.
4. Develop hybrid solar–piezo systems for higher overall generation.
5. Add microcontrollers for load management and monitoring.

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